Temporal Relationships Between Spectral Response and Agronomic Variables of a Corn Canopy

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There is growing interest in employing hand-held radiometry as a nondestructive research tool in lieu of or support of more tedious vegetation measurements The objective of this study was to evaluate such techniques on corn The spectral radiances from corn plots 1 8 m in diameter were measured using a three-band radiometer elevated 3 7 m above the ground The three spectral bands used corresponded to NASA'S Landsat-D Thematic Mapper bands TM3 (0 63–0 69 μm), TM4 (0 76–0 90 μm), and TM5 (1 55–1 75 μm) Periodically throughout the growing season a plot was selected and radiometrically measured then harvested for measurement of several agronomic variables By the end of the growing season, a total of 43 plots had been measured with solar zenith angles ranging between 16 and 44° Significant relationships were found between various combinations of the radiance data and the wet and dry total biomass, plant height, fraction of ground covered by plants, wet and dry green leaf biomass, green leaf area index fraction of leaf chlorosis, and total plant water content Some of these relationships were found to be redundant since several of the agronomic variables were highly correlated to one another In addition, the TM5 band did not provide any marked improvement in the relationships to the agronomic variables The relationships between the radiance data and agronomic variables represent a nondestructive remote sensing technique for researching the growth of corn canopies

Introduction

There is a growing group of scientists now employing hand-held radiometry as a nondestructive research tool in lieu of or support of other more tedious vegetation measurements and in turn these inferred vegetation variables are used in researching the growth and development of vegetation (Jackson et al., 1980). Past studies indicate that vegetation variables (e.g., biomass, leaf area, and percent cover) can be related to spectral radiometric data (Aase and Siddoway, 1981, Gausman et al, 1975, Holben et al, 1980, Tucker et al, 1979a,b, Wiegand et al, 1979, among others). With regard to corn, Tucker et al. (1979b) have reported the relationship of red and photographic-infrared spectral radiances to total wet and dry biomass, plant height, estimates of percent canopy cover, and visual percent chlorosis Significant relationships were reported which suggested the possibility of remote monitoring of corn canopy growth

Holben et al (1980) reported that the green leaf area index (LAI) and green leaf biomass were the soybean canopy variables most highly correlated to red and photographic-infrared spectral data and related spectral combinations Tucker

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(1979) reported that the photosynthetically active portion (green leaves) of a blue grama grass canopy was the canopy variable most highly correlated with red and photographic-infrared spectral data.

We now report on an experiment in which we have related spectral radiance data collected in three spectral regions to corn canopy variables The study extends the work of Tucker et al. (1979b) in that more detailed measurements of corn canopy variables (including wet and dry green leaf biomass, green leaf area index, chlorotic leaf biomass, chlorotic leaf area, and leaf water content, among others) were made using quantitative techniques (no visual estimates). In addition, spectral data were collected with a hand-held radiometer having Landsat-D Thematic Mapper (TM) bands TM3 (0.63–0 69 μm), TM4 (0.76–0 90 μm), and TM5 (1 55–1 75 μm) TM3, TM4, and TM5 seem to be well situated spectrally for making remotely sensed measurements related to chlorophyll concentration, leaf density, and leaf water content (Tucker, 1978)

Methods and Analyses

A field (approximately 0.9 ha) of well-drained Elkton silt loam soil located on the USDA Beltsville Agricultural Research Center was selected for this study Dekalb XL64A corn (*Zea mays* L.) was planted on 12 May 1979 in rows 76 cm apart (26 cm within the row) at a population density of approximately 50,400 plants per hectare Rows were planted in a north–south direction Before planting, the soil was limed, tilled, and fertilized (90 kg N, 39 kg P, and 74 kg K per hectare) Atrazine was applied at planting to control weeds. No additional tillage or weed control was required during the growing season

Periodically throughout the growing season several plots were randomly selected, radiometrically measured, then harvested for measurement of several agronomic variables By the end of the growing season, a total of 43 plots had been measured Table 1 presents the number of plots for each date along with the corresponding plotting symbols used in the results sections of this paper. In addition, Table 1 presents growth stage of the plots using the scale of Hanway (1963)

Each plot measured was a 2 6 m^2 circle on the ground and was centered on-row Prior to destructive sampling, the spectral radiance of each plot in Thematic Mapper (TM) bands 3 (0 63–0.69 μm), 4 (0 76–0.90 μm), and 5 (1 55–1 75 μm) were measured using a Mark II three-band radiometer (prototype) attached to a 3.7-m-high portable boom (hand-held) as described by Tucker et al. (1980). The sensor's field of view was 24° full angle (measured at one half of peak response), thus the sensor had a ground field of view essentially equivalent to the plot area. The radiometer was visually centered over each plot and the radiances for the three bands were recorded. To reduce the error caused by positioning the radiometer, it was independently centered four times over each plot and the mean for each band was calculated The coefficients of variation of these mean radiances were relatively small—on the order of 1 6, 1 1, and 0 9% for the TM3, 4, and 5 bands, respectively (mean values) All further calculations were performed with these mean radiance values. Data were collected between the hours of 1010 and 1300 EST in direct sunlight with cloud-

TABLE 1 Number of Plots Measured on Each Date with Corresponding Symbol Used in Figs 1–6 of the Results Section A Total of 43 plots Were Measured The Growth Stages of Corn Refer to the Scale of Hanway (1963)

Date	Number of Plots Measured	Growth Stage	Plotting Symbol	Date	Number of Plots Measured	Growth Stage	Plotting Symbol
06/15/79	4	(1) Collar of fourth leaf visible	A	07/31/79	2	(6) Kernels in 'blister" stage	J
06/22/79	4	(1) Collar of fourth leaf visible	B	08/06/79	2	(6) Kernels in "blister" stage	K
06/27/79	3	(1) Collar of fourth leaf visible	C	08/13/79	2	(7) Very late "roasting ear" stage	L
07/03/79	3	(1) Collar of fourth leaf visible	D	08/20/79	1	(7) Very late "roasting ear" stage	M
07/06/79	3	(2) Collar of eighth leaf visible	E	08/30/79	2	(8) Early ' dent" stage	N
07/18/79	2	(4) Collar of sixteenth leaf visible, tips of many tassels visible	F	09/04/79	2	(9) Full "dent' stage	O
07/19/79	2	(4) Collar of sixteenth leaf visible, tips of many tassels visible	G	09/11/79	2	(9) Full "dent" stage	Q
07/23/79	3	(5) Silks visible, pollen shedding	H	09/18/79	2	(9) Full "dent ' stage	R
07/27/79	2	(5) Silks visible, pollen shedding	I	10/03/79	2	(10) Grain physiologically mature	S

less or partly cloudy skies. The minimum and maximum solar zenith angles of these measurements were 16° and 44°, respectively

The individual spectral radiances for each plot were transformed into the normalized difference vegetation index (Rouse et al , 1973) for TM band combination 3 and 4 (ND34) and for TM band combination 5 and 4 (ND45) where

$$ND34 = \frac{TM4 - TM3}{TM4 + TM3},$$

and

$$ND45 = \frac{TM4 - TM5}{TM4 + TM5}$$

The ND34 transformation of raw radiance values is desirable because of its reported sensitivity to vegetation parameters and it tends to normalize the irradiance for limited solar zenith angles (Tucker et al., 1979).

A vertical photograph of each plot was taken from the portable boom, a dot grid (200 points) was applied to the photograph to obtain a quantitative estimate of the fraction of ground covered by the vegetation. The estimated maximum error bound (two times the estimated standard error of the mean proportion, maximum value at a proportion of 0.50, Mendenhall et al., 1971) was ±0.071. Other agronomic measurements prior to harvesting included mean plant height and number of leaves expanded

Immediately following the field measurements, the entire plot was harvested (approximately 13 plants + components within plots) and the following agronomic data were taken Total wet biomass was weighed, after which the plants were separated into green leaf, chlorotic leaf, stalk, tassel, and ear components and each of these components were weighed. All components were oven dried 6 days at 50°C and the dry plant material and water content weights for the components and total material were calculated All weights were presented on a per square meter of ground area basis. Prior to drying, green leaf and chlorotic leaf area indices (total one-sided leaf area per plot divided by plot ground area) were measured by using an optically integrating area meter Fraction of chlorosis was calculated as the ratio of the chlorotic leaf area index to the total leaf area index On a few occasions some of these above agronomic measurements were not taken as indicated in the results section.

A simple linear regression approach was taken in which the individual radiances and radiance transformations were correlated with the agronomic variables In addition, nonlinear relationships between selected agronomic variables and the normalized differences for the 43 plots were explored using the power function

$$T=aX^{b},$$

where T is a particular spectral transformation, X is the agronomic variables and a and b are coefficients The a and b coefficients were determined using a least squares fit of the linearized equation

$$\ln T=\ln a+b(\ln X)$$

Results and Discussion

During the 1979 growing season above average precipitation occurred and no periods of drought stress were reported Thus, no visible water stress of the corn canopy was apparent. Under these conditions, for all plot measurements the correlation coefficient (r) between TM3 and TM5 was 0 97. Thus, the temporal relationships between the various agronomic variables and ND34 and ND45 were highly redundant As a consequence, the results presented concentrate on the ND34 relationships.

A number of agronomic variables were highly correlated with each other as a result of the inherent physiology and/or anatomy of plant growth (Table 2) For example, plant height and total wet biomass were highly correlated with a r value of 0.99, and there were 26 other correlations in Table 2 with r values greater than 0 80. Because of these high interagronomic variable correlations, the relationships between spectral transformations and agronomic variables are in many cases redundant

The quantitative relationships which were shown by Tucker et al (1979a) [total wet and dry biomass and plant height versus the normalized difference of a red (0 65–0 7 μm) and near-infrared (0 775–0 825 μm) band] were very similar in all respects to the relationships found in this study. For example, Fig 1 shows the total dry biomass plotted against the ND34 Initial ND34 values were very low and by 18 July had reached a maximum, while the dry biomass continued to increase Senescence began after 20 August and the ND34 ratio and wet biomass values began to decrease The ND34 ratio decreased primarily because of leaf senescence and the reduction in canopy ground cover (Tucker et al , 1979a)

The ND34 ratio reached a maximum 18 July, whereas the wet biomass continued to increase until 20 August and

TABLE 2 Linear Correlation Coefficients (r) Between Selected, Sampled Agronomic Variables Sample sizes (n) and Levels of Significance Are Indicated

	Wet Green Leaf Biomass	Total Dry Biomass	Dry Green Leaf Biomass	Plant Height	Fraction Leaf Chlorosis[a]	Green Leaf LAI	Percent Cover	Chlorotic Wet Leaf Biomass	Chlorotic Leaf LAI	Total LAI
Total Wet Biomass	0.80[b] n=43	0.85[b] n=43	0.88[b] n=43	0.99[b] n=38	−0.65[b] n=10	0.79[b] n=41	0.91[b] n=43	0.45[b] n=43	0.36[c] n=41	0.92[b] n=41
Wet Green Leaf Biomass		0.41[b] n=43	0.98[b] n=43	0.76[b] n=38	−0.95[b] n=10	0.99[b] n=41	0.78[b] n=43	−0.08 n=43	−0.21 n=41	0.95[b] n=41
Total Dry Biomass			0.55[b] n=43	0.86[b] n=38	−0.77[b] n=10	0.37[c] n=41	0.68[b] n=43	0.79[b] n=43	0.36[c] n=41	0.61[b] n=41
Dry Green Leaf Biomass				0.85[b] n=38	−0.96[b] n=10	0.97[b] n=41	0.82[b] n=43	0.03 n=43	−0.11 n=41	0.96[b] n=41
Plant Height					−0.82[b] n=10	0.74[b] n=38	0.90[b] n=43	0.52[b] n=43	0.41[c] n=41	0.88[b] n=41
Fraction Leaf Chlorosis[a]						−0.91[b] n=10	−0.11 n=10	0.91[b] n=10	0.96[b] n=10	−0.86[b] n=10
Green Leaf LAI							0.74[b] n=43	−0.09 n=43	−0.23 n=41	0.95[b] n=41
Percent Cover								0.31 n=43	0.24 n=41	0.88[b] n=41
Chlorotic Wet Leaf Biomass									0.98[b] n=41	0.21 n=41
Chlorotic Leaf LAI										0.07 n=41

[a] Samples from 30 August to 3 October
[b] Indicates significance at the 0.01 level of probability
[c] Indicates significance at the 0.05 level of probability

thereafter decreased rapidly because of crop senescence (Fig. 2) Essentially the same trajectory was seen for ND34 versus plant height and fraction cover (Fig 3) since the correlation coefficients (r) between total wet biomass versus plant height and fraction cover were 0.99 and 0.91, respectively (Table 2).

An excellent nonlinear relationship existed between ND34 and dry green leaf biomass (Fig. 4) Because of the high positive correlation of dry green leaf biomass with wet green leaf biomass and green leaf area index (Table 2), excellent relationships of a similar trend as Fig 4 were observed between these variables and ND34 (Table 3), e g , the relationship between ND34 and green leaf area index (Fig 5). The dry green leaf biomass also had a high negative correlation with the fraction of leaf chlorosis (Table 2) A high negative correlation between the ND34 and the fraction of leaf chlorosis from the beginning of senescence (after August 20) to the final sample (October 3) is documented in Table 3 Higher correlations were obtained with the ND34 transformation than the individual TM bands 3 and 4 (Table 3) under the variable irradiance conditions of this study

Table 4 presents the linear correlation coefficients (r) for several spectral radiance transformations and agronomic variables In many cases, nonlinear relation-

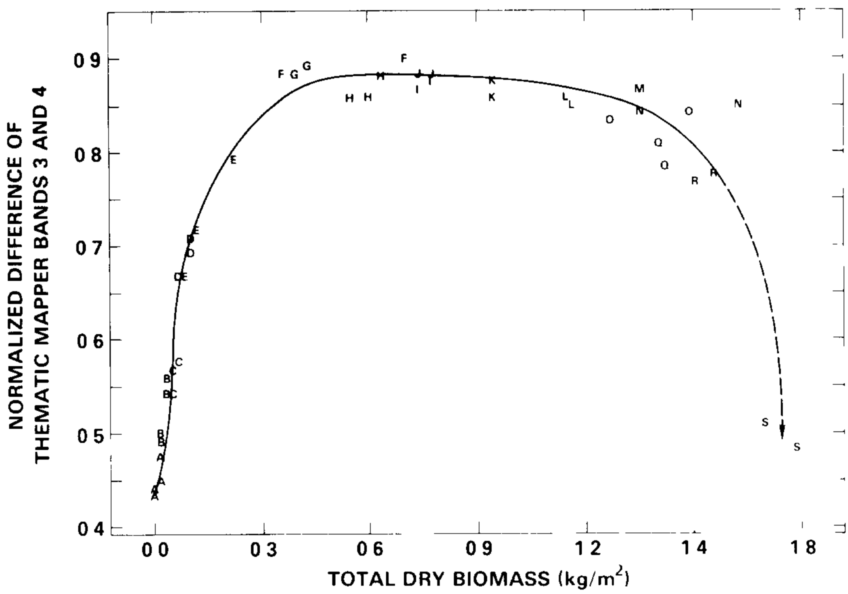

FIGURE 1 Temporal trajectory of the normalized difference of Thematic Mapper band 3 and 4 (ND34) versus total dry biomass per unit ground area Data point symbols refer to sampling dates shown in Table 1

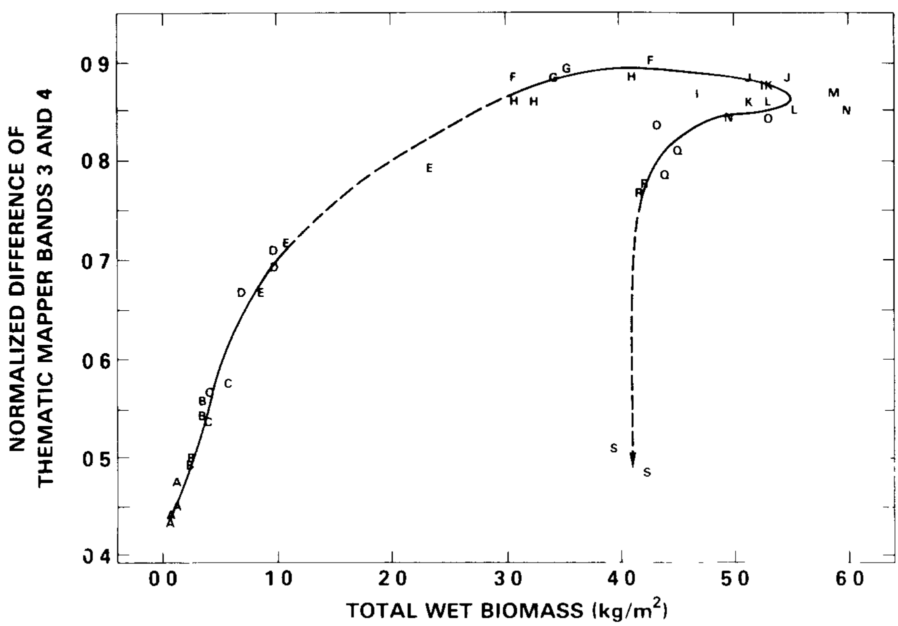

FIGURE 2 Temporal trajectory of the normalized difference of Thematic Mapper bands 3 and 4 (ND34) versus total wet biomass per unit ground area Data point symbols refer to sampling dates shown in Table 1

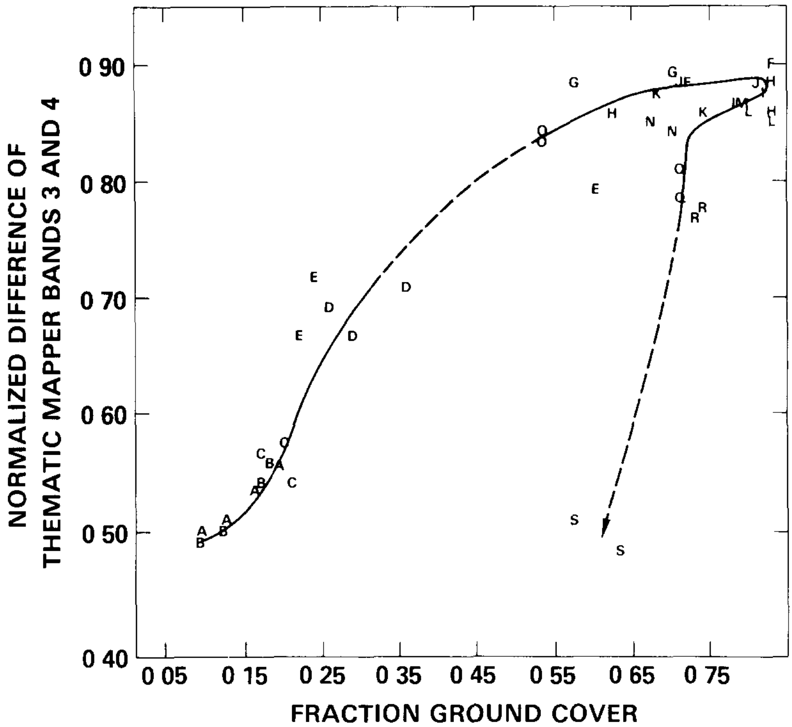

FIGURE 3 Temporal trajectory of the normalized difference of Thematic Mapper bands 3 and 4 (ND34) versus fraction of ground cover by plants Data point symbols refer to sampling dates shown in Table 1

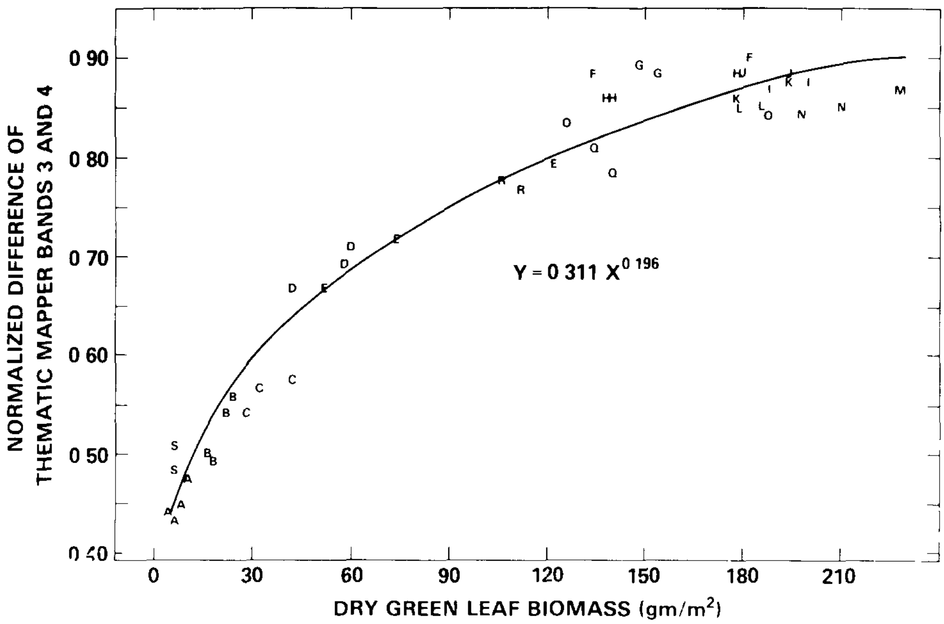

FIGURE 4 Nonlinear relationship of the normalized difference of Thematic Mapper bands 3 and 4 (ND34) versus dry green leaf biomass per unit ground area Data point symbols refer to sampling dates shown in Table 1

TABLE 3 Correlation Coefficient (r) of the Linearized Relationships (Linearization of $Y=aX^{b}$) Between Specific Agronomic Variables (X) and Three Radiometric Variables (Y) The coefficients, a and b, of the nonlinear ND34 relationships are also reported Sample sizes (n) and levels of significance are indicated

Agronomic Variable	Radiometric Variables			Coefficients	
	TM3	TM4	ND34	a	b
Wet Green Leaf Biomass	−0 76[b] $n=43$	0 44[b] $n=43$	0 95[b] $n=43$	0 225	0 198
Dry Green Leaf Biomass	−0 83[b] $n=43$	0 32[c] $n=43$	0 97[b] $n=43$	0 311	0 196
Green Leaf Area Index	−0 71[b] $n=41$	0 48[b] $n=41$	0 92[b] $n=41$	0 691	0 199
Fraction Leaf Chlorosis[a]	0 82[b] $n=10$	−0 97[b] $n=10$	−0 98[b] $n=10$	0 557	−0 210

[a]Samples from 30 August to 3 October
[b]Indicates significance at the 0 01 level of probability
[c]Indicates significance at the 0 05 level of probability

ships existed and a simple linear relationship was not representative Nevertheless, it is believed that many of the reported transformations are redundant in characterizing temporal relationships of agricultural crops

We also found that the leaf biomass determinations were highly correlated to leaf area measurements. The total LAI was highly correlated with total leaf biomass ($r=0.98$), the green LAI was highly correlated to green leaf biomass ($r=0\ 99$)

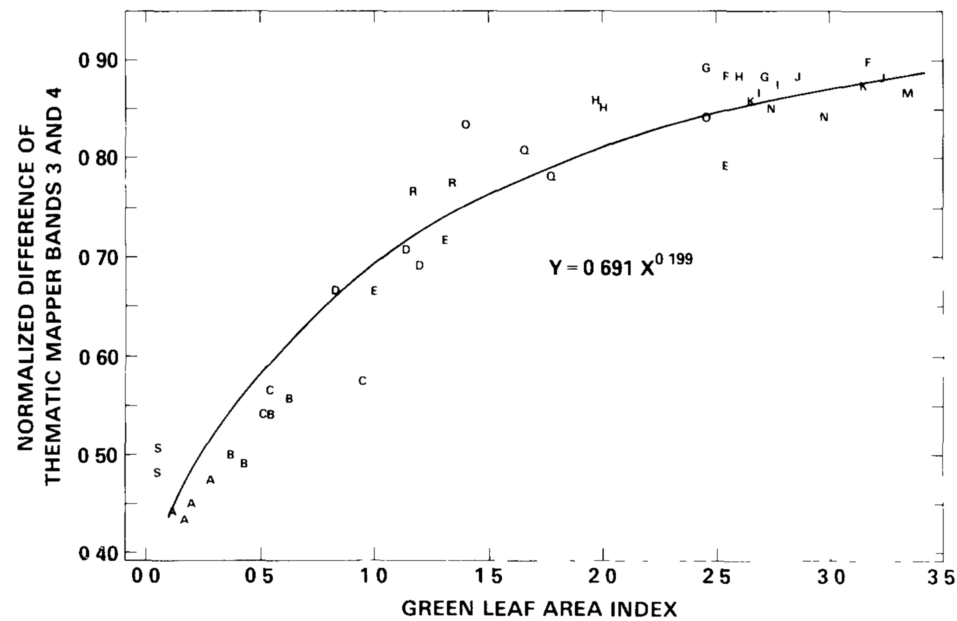

FIGURE 5 Nonlinear relationship of the normalized difference of Thematic Mapper bands 3 and 4 (ND34) versus green leaf area index Data point symbols refer to sampling dates shown in Table 1

TABLE 4 Linear Correlation Coefficients (r) for the Spectral Radiance Data and Agronomic Variables. The sample sizes are noted in parentheses.[a] Levels of significance are indicated.

AGRONOMIC VARIABLE	RADIOMETRIC VARIABLES							
	TM3	TM4	TM5	$\frac{TM4}{TM3}$	$\frac{TM4}{TM5}$	$\frac{TM4}{TM3+TM5}$	$\frac{TM4-TM3}{TM4+TM3}$	$\frac{TM4-TM5}{TM4+TM5}$
Green LAI (41)	−0.80[c]	0.29[c]	−0.85[c]	0.94[c]	0.91[c]	0.95[c]	0.93[c]	0.92[c]
Green wet leaf biomass (43)	−0.83[c]	0.31[d]	−0.87[c]	0.95[c]	0.90[c]	0.96[c]	0.96[c]	0.93[c]
Green dry leaf biomass (43)	−0.84[c]	0.21	−0.89[c]	0.92[c]	0.89[c]	0.94[c]	0.94[c]	0.91[c]
Chlorotic LAI (41)	−0.29	−0.83[c]	−0.18	−0.16	−0.25	−0.20	−0.09	−0.40[c]
Chlorotic wet leaf biomass (43)	−0.39[c]	−0.81[c]	−0.29[d]	−0.04	−0.15	−0.09	−0.04	−0.26
Chlorotic dry leaf biomass (43)	−0.24	−0.83[c]	−0.13	−0.19	−0.28	−0.23	−0.14	−0.45[c]
Total LAI (41)	−0.90[c]	0.05	−0.92[c]	0.90[c]	0.85[c]	0.92[c]	0.93[c]	0.82[c]
Total wet leaf biomass (43)	−0.89[c]	0.16	−0.92[c]	0.94[c]	0.87[c]	0.94[c]	0.96[c]	0.88[c]
Total dry leaf biomass (43)	−0.91[c]	−0.18	−0.91[c]	0.79[c]	0.73[c]	0.79[c]	0.84[c]	0.66[c]
Wet stalk biomass (43)	−0.91[c]	−0.15	−0.90[c]	0.85[c]	0.74[c]	0.84[c]	0.84[c]	0.65[c]
Dry stalk biomass (39)	−0.74[c]	−0.45[c]	−0.68[c]	0.46[c]	0.40[d]	0.46[c]	0.44[c]	0.16
Total wet biomass (43)	−0.88[c]	−0.17	−0.89[c]	0.78[c]	0.75[c]	0.80[c]	0.80[c]	0.65[c]
Total dry biomass (43)	−0.69[c]	−0.56[c]	−0.66[c]	0.38[d]	0.34[d]	0.39[d]	0.46[c]	0.24
Plant water content (43)	−0.88[c]	−0.02	−0.91[c]	0.87[c]	0.85[c]	0.89[c]	0.87[c]	0.75[c]
Canopy cover (39)	−0.90[c]	−0.07	−0.88[c]	0.80[c]	0.70[c]	0.79[c]	0.81[c]	0.60[c]
Fraction leaf[b] chlorosis (10)	0.94[c]	−0.96[c]	0.95[c]	−0.98[c]	−0.96[c]	−0.98[c]	−0.99[c]	−0.99[c]

[a]Only the linear correlation coefficients are reported in this table. We acknowledge that nonlinear relationships existed in many cases. This is further discussed in the text.
[b]Samples from 30 August to 3 October.
[c]Indicates significance at the 0.01 level of probability.
[d]Indicates significance at the 0.05 level of probability.

and the chlorotic LAI was highly correlated to chlorotic wet leaf biomass ($r=0.98$). Similar findings have been reported for winter and spring wheat (Aase, 1978; LeMaster et al., 1980) and for soybeans (Holben et al., 1980). We thus feel, as does Aase (1978), that leaf biomass measurements can replace the more tedious LAI determinations. In addition, we also observed significantly lower correlations between the commonly recorded agronomic variable, estimated crop cover, and the spectral data than was the case with the spectral data and the green LAI and green biomass data (Table 4) since estimations of the crop canopy cover include both green and chlorotic plant components.

Conclusions

Bands TM3 and TM5 were highly correlated ($r=0.97$); thus these two bands appear to contain redundant information under these conditions where we observed no plant water stress.

Green leaf biomass determinations were highly correlated with the green leaf area index Similar relationships were found between total leaf biomass and total LAI as well as between chlorotic leaf biomass and chlorotic LAI. This observation suggests that component biomass measurements can be substituted for the more tedious LAI measurements and still provide quantitative data highly correlated with corn canopy spectral response In addition, many of the other agronomic variables were highly interrelated because of their relationship(s) to crop growth

The green leaf area index and green leaf biomass were found to be the best correlated agronomic variables with the spectral data. The commonly recorded agronomic variable, estimated canopy cover (both green and chlorotic components), was less well correlated Significant relationships were also found between single band spectral radiances and associated multiband combinations and many of the other agronomic variables sampled

Our overall conclusions is that nondestructive ground-based remote sensing techniques can be applied to corn canopies to estimate agronomic variables highly related to corn canopy physiological status

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